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Spatio-temporal segmentation of mesoscale ocean surface dynamics using satellite data

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Abstract—Multi-satellite measurements of altimeter-derived Sea Surface Height (SSH) and Sea Surface Temperature (SST) provide a wealth of information about ocean circulation, especially mesoscale ocean dynamics which may involve strong spatio-temporal relationships between SSH and SST fields. Within an observation-driven framework, we investigate the extent to which mesoscale ocean dynamics may be decomposed into a superimposition of dynamical modes, characterized by different local regressions between SSH and SST fields. Formally, we develop a novel latent class regression model to identify dynamical modes from joint SSH and SST observation series. Applied to the highly dynamical Agulhas region off South Africa, we demonstrate and discuss the geophysical relevance of the proposed mixture model to achieve a spatio-temporal segmentation of the upper ocean dynamics.

I. INTRODUCTION

In the last two decades, multi-satellite measurements of altimeter-derived Sea Surface Height (SSH) and multi-sensor measurements of Sea Surface Temperature (SST) have provided a wealth of information about ocean circulation and atmosphere-ocean interactions. As a depth-integrated quantity dependent upon the density structure of the water column, altimeter SSH estimations capture mesoscale structures, horizontal scales of 50 km to few hundred kilometers, and allow to retrieve surface currents using the geostrophy balance. This emerging and rich mesoscale circulation further stirs the large-scale SST fields. Accordingly, our picture of upper ocean dynamics has considerably evolved towards a complex system characterized by strong interactions, whose spatio-temporal variability extends over a wide range of scales. Furthermore, several studies (see e.g. [12] or [9]) rationalize and demonstrate that fields of SST can become an active tracer coupled to the dynamics leading to strong correlations with SSH fields. To these assumptions the upper ocean dynamics may be simply predicted from surface density horizontal variations possibly dominated by SST variations. For such a case, a linear transfer function shall be identified between SSH and SST fields (cf. [8]).

Within an observation-driven framework, one may consider joint PCA/EOF (Principal Component Analysis, Empirical Orthogonal Functions) procedures to decompose the relationships between SST and SSH fields, as widely used in ocean sensing applications (cf. [13], [2]). Such EOF-based schemes would

however resort to a single linear and global model. As such, this model could not address the spatial non-stationarity of the SST-SSH relationships. By contrast, we here consider local linear transfer functions. We assume that locally, upper ocean dynamics may be analyzed according to a finite mixture model, where each component of the mixture is characterized by a local SST-SSH linear transfer function. This mixture-based representation relates to a nonlinear model. In this paper, we propose to investigate such a model to (i) develop a probabilistic learning-based setting for the inference of such mixture models and the spatio-temporal segmentation of the identified dynamical modes (i.e., the different components of the mixture model), and (ii) evaluate the extent to which such mixture models are geophysically relevant to characterize the upper ocean dynamics over active ocean regions.

Hereafter we consider the Agulhas region. The paper is organized as follows. Section II presents the remote sensing data. Section III describes our probabilistic learning-based model. In Section V, the application to satellite observations is evaluated. We further discuss and summarize the key results of our investigations in Section VI.

II. DATA

As SSH and geostrophic surface current (U,V) data, we use the daily delayed time Maps of Absolute Dynamic Topography (MADT) produced by Collecte Localisation Satellites (CLS) available online at <http://www.aviso.oceanobs.com/>. This information combines the signal of several altimeters onto a 1/3 degree Mercator projection grid. We use the 2004 data since four altimeters were available (Jason-1, Envisat or ERS-2, Topex/Poseidon and GFO). As SST data, we use optimally interpolated microwave SSTs provided by Remote Sensing System (RSS) available online at <http://www.ssmi.com/>. It combines the signal of three microwave radiometers (TMI, AMSR-E and WindSAT) which are robust to the presence of clouds. The spatial resolution is $1/4 \times 1/4$ degrees and the temporal resolution is the same as the MADT data, i.e. daily. We bilinearly interpolate the MADT data onto the SST grid. We focus on the Agulhas region between longitudes 5°E to 65°E and latitudes 30°S to 48°S . An example of SST and SSH fields with the associated geostrophic currents are given in Fig. 1.

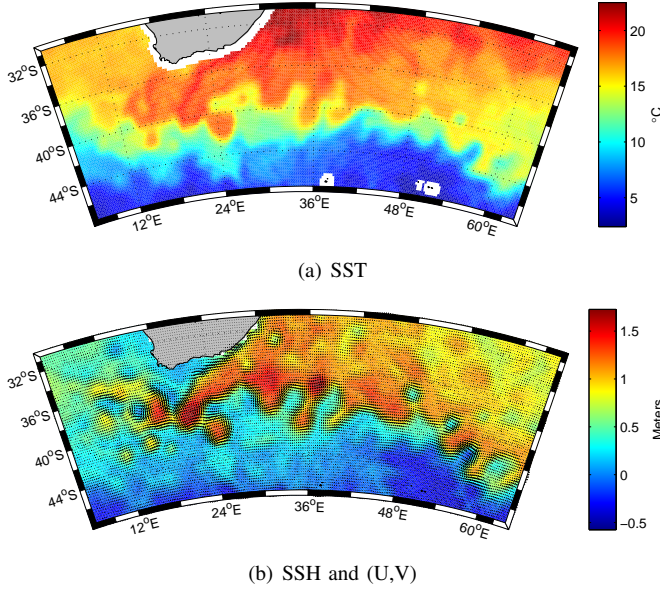


Fig. 1. Satellite data of SST (a) and SSH with the associated geostrophic surface currents (b) the 1st of September, 2004 within the Agulhas current.

III. METHODOLOGY

A. Patch-based approach

As mentioned above, recent theoretical and numerical experiments have stressed that upper ocean dynamics may be characterized by couplings between SSH and SST according to the following relationship in the Fourier domain (cf. [7]):

$$\mathcal{F}_{\mathcal{H}}(\widehat{\text{SSH}}) = -\gamma|\mathbf{k}|^{-\alpha}\mathcal{F}_{\mathcal{T}}(\widehat{\text{SST}}) \quad (1)$$

where \mathbf{k} is the horizontal wavenumber vector, $\mathcal{F}_{\mathcal{H}}$ and $\mathcal{F}_{\mathcal{T}}$ are linear filters of SSH and SST respectively. The α parameter sets up the effective coupling between surface fields. For $\alpha = 1$, Eq. (1) resorts to the Surface Quasi-Geostrophy (SQG) model. In [8], $\mathcal{F}_{\mathcal{H}}$ and $\mathcal{F}_{\mathcal{T}}$ were band-pass filters between 80 km and 300 km. As α increases, the smoothing increases and couplings decreases. For $\alpha = 2$, the filtered SST would trace the vorticity. Formally, Eq. (1) states that surface currents can be regarded as spatial derivatives of a filtered version of the SST field. The parameter γ relates to a normalization constraint. In general, parameters γ and α as well as the definition of the filters $\mathcal{F}_{\mathcal{H}}$ and $\mathcal{F}_{\mathcal{T}}$, may spatially vary such that a single linear transfer function as in Eq. (1) is unlikely to apply globally.

These considerations led us to hypothesize that zonal and meridional geostrophic surface currents (U,V) and SSH can still locally relate to SST derivatives, but according to a finite set of K linear transfer functions, hereafter referred to as K dynamical modes. Formally this is stated in the Fourier domain as

$$\widehat{\text{SSH}} = \mathcal{H}_k(\widehat{\text{SST}}) \quad (2)$$

where \mathcal{H}_k now characterizes the k^{th} dynamical mode, which locally relates SSH and SST fields through linear filter \mathcal{H}_k .

Using a matrix formulation, Eq. (2) is rewritten in the real domain as a patch-based linear regression

$$\mathbf{Y}(s, t) = \mathbf{H}_k(s, t)\mathbf{X}(s, t) \quad (3)$$

where $\mathbf{Y}(s, t)$ encodes the local SSH variability through a 3-dimensional vector formed by the SSH value and the surface current (U,V) at spatio-temporal location (s, t) and $\mathbf{X}(s, t)$ is the vectorized version of the local SST patch centered in s at time t (cf. Fig. 2). It may be noted that we encoded local SSH variations at spatio-temporal location (s, t) through the surface currents which are computed as the spatial derivatives of the SSH field. As such, it constrains the method to account for spatial regularity. The $p \times 3$ regression coefficient matrix $\mathbf{H}_k(s, t)$ associated with dynamical mode k is corresponding to the local version of \mathcal{H}_k in Eq. (2). It corresponds to three vectorized versions of spatial convolution matrices. Here, p defines the size of the local SST neighborhood and is set according to the Rossby radius of the study region, *i.e.* the mean size of the mesoscale ocean structures like eddies. For the Agulhas current region, we set it up to 200 km, *i.e.* $p = 81$ for the spatial resolution of the considered data.

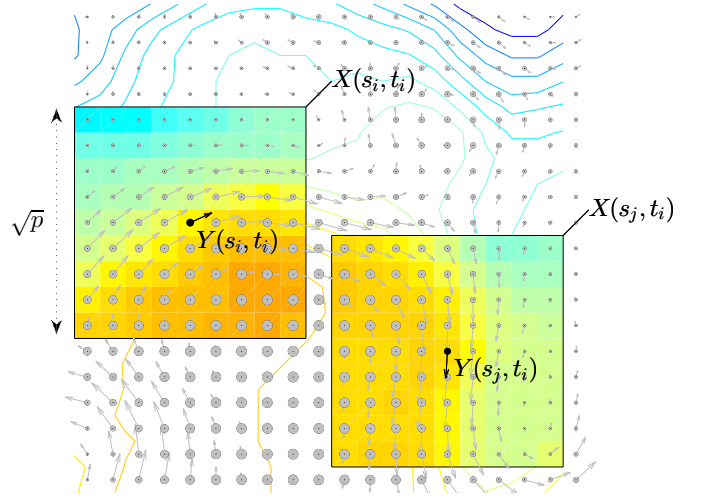


Fig. 2. Sketch of SST patches (contour plot), noted \mathbf{X} , and the corresponding SSHs (scatter plot) and surface currents (quiver) noted \mathbf{Y} at the central location s_i and s_j at time t_i .

B. Latent class regression model

Our objective is to identify K different hidden surface dynamical modes from a joint set of SST patches (p -dimensional vector \mathbf{X}) and SSH with the associated zonal and meridional surface currents (3-dimensional vector \mathbf{Y}) as illustrated in Fig. 2. We assume that the conditional likelihood of \mathbf{Y} given \mathbf{X} resorts to a mixture of Normal distributions such as

$$p(\mathbf{Y}|\mathbf{X}, \boldsymbol{\theta}) = \sum_{k=1}^K \lambda_k \mathcal{N}_k(\mathbf{Y}; \mathbf{X}\boldsymbol{\beta}_k, \boldsymbol{\Sigma}_k) \quad (4)$$

where \mathcal{N}_k represents a multivariate Gaussian probability density function with mean $\mathbf{X}\boldsymbol{\beta}_k$ and covariance $\boldsymbol{\Sigma}_k$, and λ_k is the prior probability of mode k . In the literature,

this model is referred to as a “latent class regression” or “clusterwise regression” (cf. [5]). To simplify the notations, we store the overall parameters of the model in $\theta = (\lambda_1, \dots, \lambda_K, \beta_1, \dots, \beta_K, \Sigma_1, \dots, \Sigma_K)$ and estimate them using a classical maximum likelihood criterion (see [4] for more details). Then, we exploit the inferred model with parameters $\hat{\theta}$ to perform a spatio-temporal segmentation of the underlying dynamical modes. More precisely, for any spatial location s and time t , using the Bayes’ theorem, we evaluate the posterior likelihood that the dynamical mode is of type k such as

$$\hat{\pi}_k(s, t) = \frac{\hat{\lambda}_k \mathcal{N}_k(\mathbf{Y}(s, t); \mathbf{X}(s, t) \hat{\beta}_k, \hat{\Sigma}_k)}{p(\mathbf{Y}(s, t) | \mathbf{X}(s, t), \hat{\theta})}, \forall k. \quad (5)$$

IV. RESULTS

A. Spatio-temporal segmentation

From the posterior likelihoods $\hat{\pi}_k$, we determine the segmentation maps of each dynamical mode as illustrated in Fig. 3 for a given date. The animations of the time series of these daily maps in the Agulhas current over 2004 are available on-line at: <http://tandeo.wordpress.com/communications/articles/>. A qualitative analysis of these maps of posterior likelihoods highlights a clear spatio-temporal segmentation of the different dynamical modes that can be interpreted from a geophysical perspective in terms of different geophysical processes.

V. CHARACTERIZATION OF OCEAN SURFACE DYNAMICS

For each dynamical mode, we report the observed distributions of current, height and temperature values (cf. Fig. 4). The first dynamical mode (red) characterizes very strong current magnitude and warm waters. It is primarily associated with the main Agulhas current that flows down the East coast of Africa through the Agulhas ridge. This mode also involves mesoscale eddies, the so-called warm core Agulhas rings with strong surface currents, low temperature gradients and middle-range SSH values around 0.5 m. The later seems to be a discriminative feature of this first mode. The second dynamical mode (green) mainly relates to the eastward Agulhas return current that hits a part of the South Atlantic current. It creates a subtropical front varying from 36°S to 44°S with strong eastward currents, middle-range SST gradients and large SSH values (about 1 m). The third (cyan) and fourth (blue) dynamical modes correspond to weaker surface currents. The third one is characterized by mid-temperatures and westward currents whereas the fourth one involves colder temperatures and eastward currents. Let us stress that the third dynamical mode involves large SST gradients but weak surface currents. In this mode, the SST can be clearly identified as a passive tracer of the surface upper ocean dynamics.

VI. CONCLUSION AND PERSPECTIVES

In this paper, we proposed an observation-driven framework to identify, characterize and track ocean surface dynamical modes. We rely on a latent class regression model, where the dynamical modes are characterized by a local linear

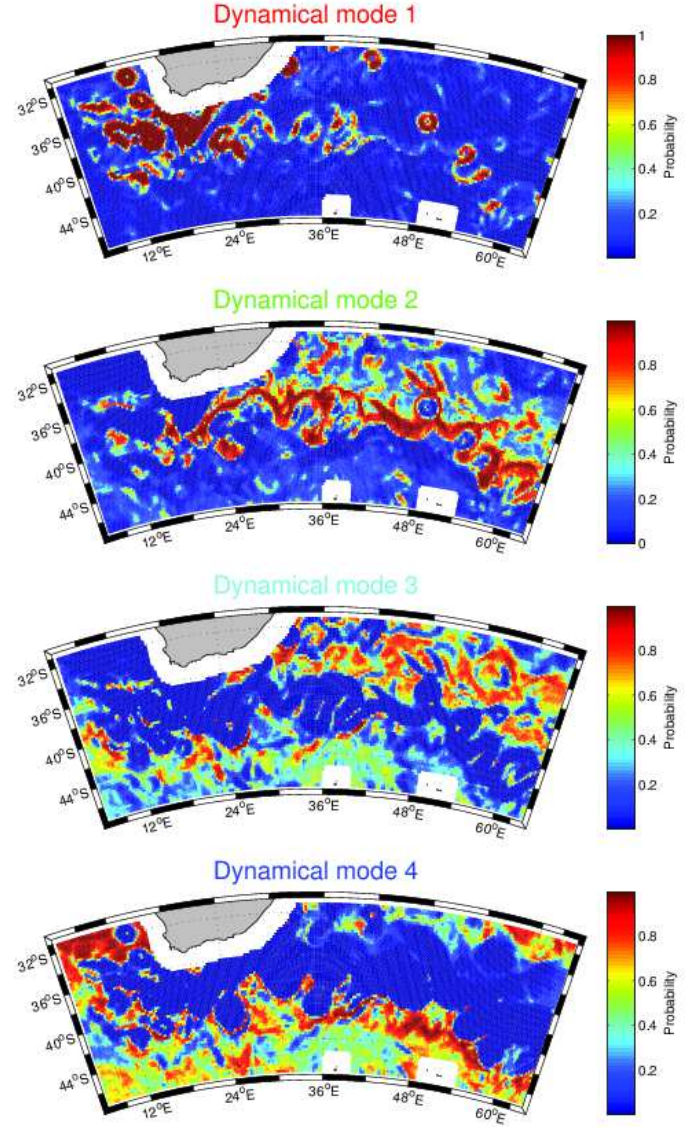


Fig. 3. Maps of the posterior likelihoods given in Eq. (5) of the dynamical modes given the SST and SSH fields, the 1st of September, 2004 within the Agulhas current. We use a four-class latent regression model fitted from the whole year 2004 (see text for details). For a given location and time, the sum of the of the four probabilities is equal to 1. In the subsequent, colors red, green, cyan and blue respectively distinguish the first, second, third and fourth dynamical modes.

transfer function between SST, SSH and surface geostrophic current (U,V). This probabilistic approach locally relates the distribution of the SSH and sea surface currents conditionally to the SST via a nonlinear model: a Gaussian mixture of linear transfer functions. The statistical parameters of the model are estimated using a maximum likelihood approach.

We applied the proposed methodology to the 2004 daily $1/4^\circ \times 1/4^\circ$ satellite SST and SSH image series. The reported results retrieved a relevant spatio-temporal decomposition of ocean surface dynamics in the Agulhas region according to four dynamical modes: (i) the main Agulhas current and warm core rings characterized by strong currents and hot

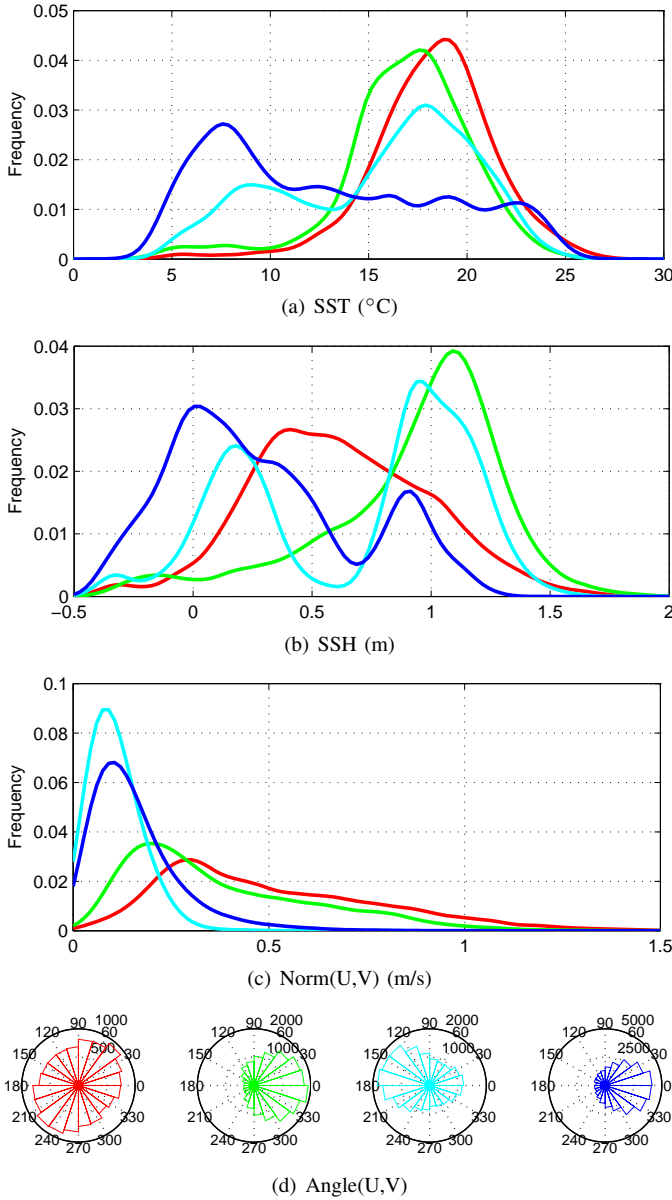


Fig. 4. Distribution of the SST (a), SSH (b), surface current (U,V) norm (c) and direction (d). The results are given for each dynamical mode within the Agulhas current for the whole year 2004.

temperatures where the SST is weakly correlated with SSH, (ii) the return Agulhas current with lower temperatures and currents where the SST is an active tracer, (iii) local front regions where strong SST gradients do not seem to affect the current velocities, and (iv) a weaker dynamical mode where SST is strongly correlated to SSH.

Our study complements previous theoretical studies which showed that mesoscale upper ocean dynamics may be characterized by a linear coupling between SST and SSH (cf. [11], [12], [9], [10], [6]). Following a fully observation-driven framework, the proposed latent regression model enabled us to identify different dynamical modes and to track the space-time extension of each dynamical mode. The reported results

clearly pointed out the requirement for considering a mixture model to decompose the space-time variabilities of the ocean surface dynamics. Regarding methodological aspects, it may be pointed out that EOF-based schemes (cf. [13], [2]) could not reveal such non-stationary space-time variabilities. Joint EOF scheme typically decomposes a global linear mapping between the analyzed fields according to principal modes.

Regarding our future work, we will further investigate latent class regression models with additional regressors. Among others, it seems appealing to explore how time-lagged SST features and other geophysical fields such as wind speed and chlorophyll-a concentration could improve the estimation of SSH and surface currents. We also plan to apply the proposed model to other strongly active ocean regions such as the Gulf Stream system. Our objective will be to determine shared and/or system-specific dynamical modes. Future work will also investigate more detailed physical interpretation of the identified dynamical modes, especially in terms of spectral characteristics. Besides, such an improved model shall then possibly address both (i) the higher resolution prediction of mesoscale ocean surface currents from SST spatio-temporal fields (cf. [3]), and (ii) the extraction of new local and global descriptors of ocean surface dynamics from satellite sea surface observations (cf. [1]).

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